Mechanical Design and Stress Analysis Challenges Overcome to Ensure the Structural Integrity of Europa Clipper's Mechanical Pumped Fluid Loop Heat Redistribution System (HRS)

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Launching in 2023, NASA's Europa Clipper mission will place a spacecraft into a long, looping orbit around Jupiter to perform a series of close flyby investigations of its moon Europa. Strong evidence suggests that Europa hosts an ocean of liquid water beneath its icy crust that could harbor conditions favorable for life. The spacecraft is currently under development by the Jet Propulsion Laboratory (JPL) and the Applied Physics Laboratory (APL) and nearing completion of its Detailed Design Phase. A Mechanical Pumped Fluid Loop (MPFL) architecture known as the Heat Redistribution System (HRS) has been baselined to provide power efficient thermal control of the sensitive components within the Avionics, Radio Frequency (RF), and Propulsion Modules. Principally, the HRS harvests waste heat from the onboard dissipating equipment and distributes it to a 1.4 m diameter by 3 m tall cylindrical structure that cocoons and keeps the propulsion subsystem warm. Numerous technical issues had to be resolved in order to securely attach nearly 100 m of HRS tubing to the spacecraft, which is predicted to experience high launch loads. This paper will review the relevant environments and mission constraints as well as outline the stress and fatigue analysis approach taken to verify the detailed mechanical design of the HRS.

Nomenclature

AFT	=	Allowable Flight Temperature
AM	=	Avionics Module
APL	=	NASA Applied Physics Laboratory
ASD	=	Acceleration Spectral Density
CBE	=	Current Best Estimate
CC	=	Contamination Control
CFC-11	=	Trichlorofluoromethane (Freon)
CLA	=	Coupled Loads Analysis
CTE	=	Coefficient of Thermal Expansion
D.O.C.	=	Degrees of Constraint
DMA	=	Dynamic Mechanical Analysis
DSN	=	Deep Space Network
EC	=	Europa Clipper
ECIPA	=	Europa Clipper Integrated Pump Assembly
ERD	=	Environmental Requirements Document
ESD	=	Electrostatic Discharge
FA	=	Flight Acceptance
FEM	=	Finite Element Model
FS	=	Factor of Safety
GD&T	=	Geometric Dimensioning and Tolerancing

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GSFC	=	NASA Goddard Space Flight Center
HGA	=	High Gain Antenna
HRS	=	Heat Redistribution System
JPL	=	NASA Jet Propulsion Laboratory
MAC	=	Mass Acceleration Curve
MMAC	=	Modal Mass Acceleration Curve
MPFL	=	Mechanical Pumped Fluid Loop
MS	=	Margin of Safety
NASA	=	National Aeronautics and Space Administration
PBE	=	Probable Best Estimate
PF	=	Proto-flight
PM	=	Propulsion Module
PP	=	Planetary Protection
REM	=	Rocket Engine Module
RF	=	Radio Frequency
RHB	=	Replacement Heater Block
RWA	=	Reaction Wheel Assembly
RSS	=	Root Sum Squaring
SDOF	=	Single Degree of Freedom
SLS	=	Space Launch System (Launch Vehicle)
TMA	=	Thermomechanical Analysis
UTS	=	Ultimate Tensile Strength

I. Introduction

NASA's Europa Clipper (EC) Mission is planning to launch in 2023 to begin its journey to Europa, a moon orbiting Jupiter that has an icy crust and potentially a vast ocean of liquid water below the surface. EC's complex instruments will take measurements that will allow scientists on Earth to determine the makeup of the moon and evaluate whether Europa hosts signs indicative of the possibility of life.

EC is a collaboration between NASA centers including the Jet Propulsion Laboratory (JPL), the Applied Physics Laboratory (APL), and Goddard Space Flight Center (GSFC). JPL and the Deep Space Network (DSN) will manage communications and data from the mission. Europa Clipper will be the first outer planet mission to use a single phase mechanically pumped Heat Redistribution System (HRS) to regulate the core temperatures on the spacecraft. The HRS was selected as EC's primary thermal architecture specifically due to its ability to harvest and conserve significant amounts of waste heat once at Europa (~5 A.U.) where the solar powered spacecraft is quite limited on power. This paper will focus on the mechanical design and analysis of the Europa Clipper HRS plumbing and all of the secondary support structure required to keep the HRS design working after launch. Some guiding principles and

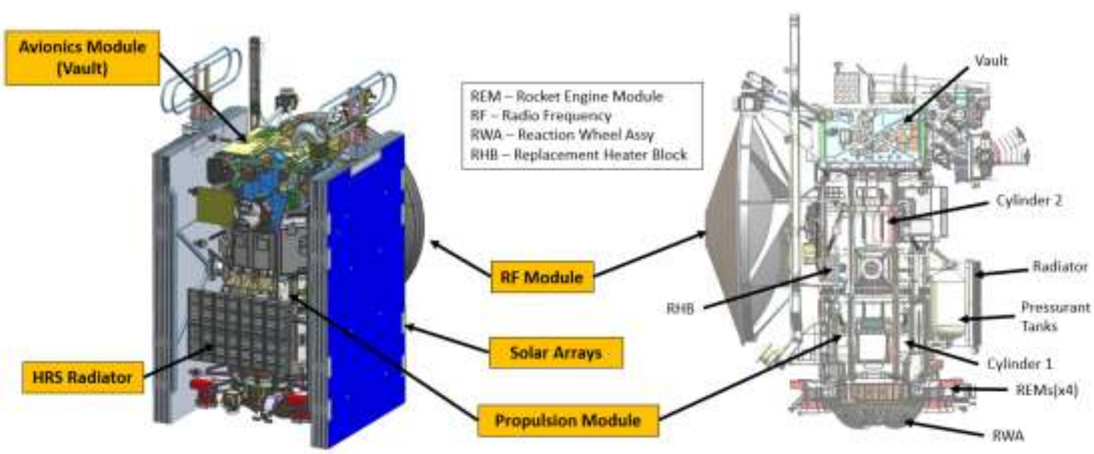


Figure 1. Europa Clipper spacecraft and its modules (at left with solar arrays stowed, and at right with solar arrays removed for clarity).

relevant materials data will be highlighted as well. Additional literature for other aspects of the HRS including its development for EC can be found in References 1-14.

II. Europa Clipper Spacecraft Overview

As shown in Fig. 1, the EC Spacecraft consists of three modules:

1. ***Avionics Module (AM)*** - a radiation hardened thick aluminum paneled vault which contains the majority of the onboard avionics and payload electronics,

2. ***Propulsion Module (PM)*** – comprised of two 1.3 m diameter cylinders that surround the main propulsion fuel and oxidizer tanks and provide an interface to the launch vehicle, four Rocket Engine Modules (REMs) which house 8 roll and 16 axial thrusters, and 1 Reaction Wheel Assembly (RWA) which closes out the bottom of the PM structure and hosts 4 reaction wheels,

3. ***Radio Frequency (RF) Module*** that contains a High Gain Antenna (HGA), and all of the necessary telecom equipment for earth communication and data transfer.

The HRS runs throughout all the various modules picking up heat from dissipating components within the Avionics and RF Modules, redistributing it to the Propulsion Module, and rejecting unwanted heat only when necessary through a large radiator. APL has been responsible for the development of the Propulsion and RF Modules whereas JPL has

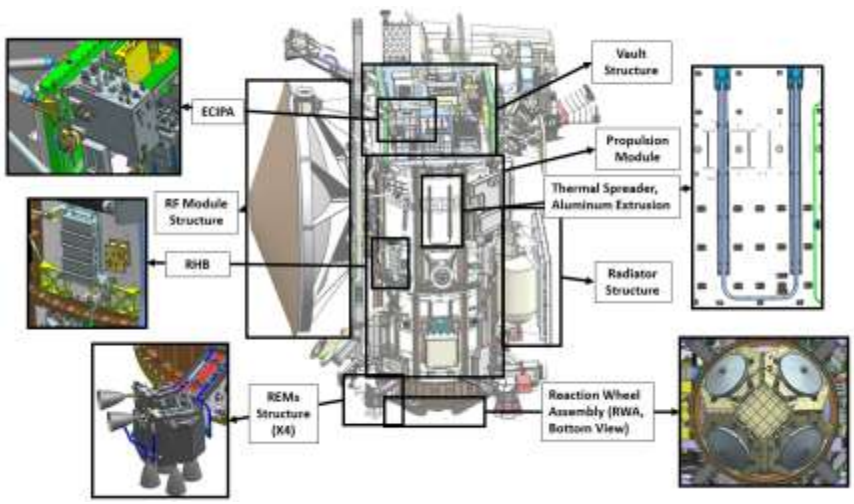


Figure 2. Mechanical configuration of the HRS

primary responsibility for the overall mission, the Avionics Module, as well as overall cognizance of the HRS.

III. HRS Mechanical Configuration

The purpose of the Europa Clipper HRS is to regulate the temperature on the Europa Clipper. To be effective, the system must:

- Remove thermal energy from relatively hot parts of the spacecraft
- Transfer thermal energy to relatively cold parts of the spacecraft
- Generate supplemental heat when the overall temperature of the spacecraft is too low
- Reject heat from the spacecraft when the overall temperature of the spacecraft is too high

To achieve the thermal requirements, Europa Clipper uses a mechanically pumped CFC-11 refrigerant circulation system that consists of several hardware elements shown in Fig. 2 that serve the following four functions:

1. **Fluid Flow.** The heart and brains of the HRS resides in the Vault and is known as the ECIPA (Europa Clipper Integrated Pump Assembly). ECIPA contains the primary and redundant pumps for circulating the working fluid around the entire spacecraft, and it also houses the primary and redundant pair of passive mixing valves for shutting off flow to the radiator structure during outer cruise and most of the Jupiter tour.

2. **Heat Acquisition/Redistribution.** Waste heat is collected from dissipating components within the Avionics and RF Modules and then redistributed to cooler parts of the spacecraft on the Propulsion Module using thermal spreaders that are bonded to critical interfaces.

3. **Supplemental Heat Generation.** When there is an insufficient amount of avionics or telecom equipment dissipation to harvest and spread to the Propulsion Module, a supplemental heat source called the Replacement Heater Block (RHB) provides electrical heat input to the working fluid via a compact cold plate heat exchanger populated with a bank of Dale Ohm heaters.

4. **Heat Rejection.** Heat rejection to space via a 1.7m^2 louvered radiator structure happens only when required. The HRS is designed to reject upwards of 320W when the spacecraft is at its closest approach to

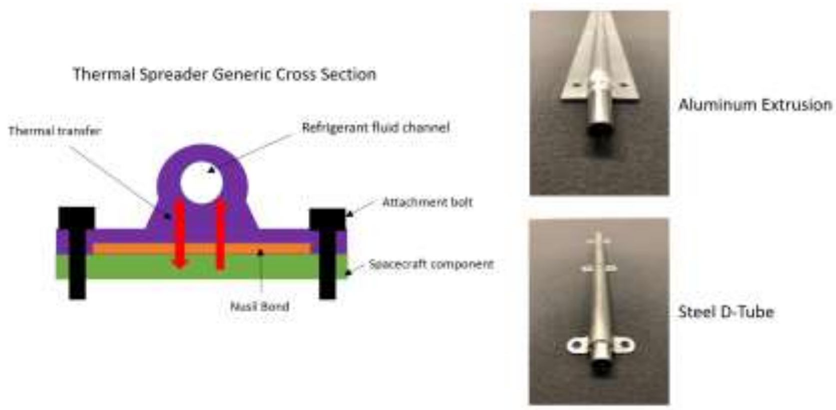


Figure 3. Two kinds of thermal spreaders used for HRS heat acquisition and redistribution – aluminum flanged extrusions and stainless steel D-tubes.

the sun during its inner cruise (0.65 A.U.). When the spacecraft is far from Earth during the Jupiter tour (~5 A.U.), the HRS then turns down the radiator heat rejection to less than 15W by passively diverting fluid flow away from the radiator (with its louvers fully closed). Most of the 15W is required to prevent freezing of the CFC-11 in the radiator circuit.

While there are many individual parts and assemblies that go into an HRS, here are some of the more common mechanical elements that are used in EC's HRS:

- **Thermal Spreaders.** As shown in Fig. 3, heat is transferred to or from the working fluid using thermal spreaders that are bonded and bolted to critical interfaces requiring thermal control. Typically, thermal spreaders are designed with a material that has high thermal conductivity, like aluminum, in order to maximize heat transfer to and from the working fluid that runs through it. A Nusil CV 2946 bond is used to help facilitate heat transfer between the spreader and its interface using a wider flanged or thinner flat D-tube profile that is intended to keep the bond line thermal resistance small. Most of the flanged thermal spreaders on Europa Clipper are made from Al-6063, and since they are fabricated using a die extrusion process, they are commonly referred to as extrusions. While they provide superior heat transfer, their practical use necessitates aluminum hand welded interfaces that may require additional bracing for strength. However, in places where access for hand welding and bracing was restricted and higher material strength was required, machined 316L steel D-tubes were implemented as an alternative. While the 316L

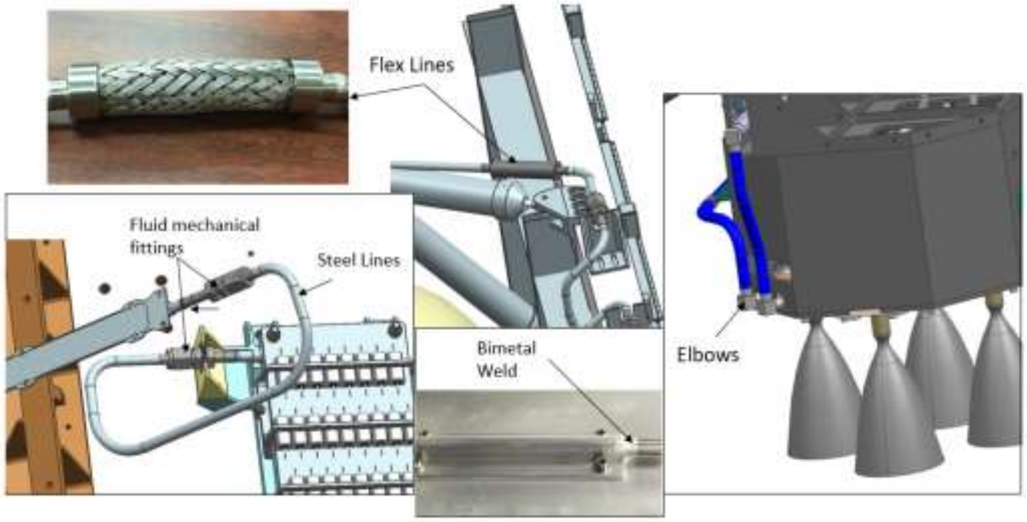


Figure 4. Various HRS stainless steel interconnects.

D-tubes are less thermally efficient, they perform adequately in their short length installations on the REMs.

- **Stainless Steel Interconnects.** For fluid flow conduits between the aluminum extrusions and other HRS components, a variety of stainless steel interconnecting hardware (refer to Fig. 4) was implemented:

  - ***316L stainless steel tubing*** is used as the main connection hardware between extrusions and sub-elements. The steel lines are bent as needed to conform to the design. Strain relief is possible by heat treatment, but analysis has shown that this is not necessary. Stainless steel tubing is used instead of aluminum because automatic orbital welding is much more reliable compared to aluminum hand welding, and steel is highly ductile and displays superior fatigue strength as compared to aluminum alloys. Steel transfer lines have the additional benefit that they provide an adiabatic boundary, reducing unnecessary heat transfer to and from the working fluid between connection points. While titanium interconnects could theoretically serve the same purpose, it is important to mention that steel was originally selected for past missions because the wetted surfaces of the pump and valve hardware were made from steel. Thus, the long-term chemical compatibility of CFC-11 and titanium has not been well characterized at JPL (flight heritage dataset is for steel and aluminum) and an effective method for welding titanium to aluminum tubing also has no heritage in JPL flagship missions.
  - ***Bimetallic fittings*** contain a stainless steel to aluminum inertial weld and are the components which are hand welded to the aluminum extrusions in order to transition the interconnect plumbing to steel.
  - ***Flex lines*** are used in locations where predicted relative displacements between plumbing assemblies are excessive enough to overstress any reasonably compliant steel line interconnect containing a few bends. However, flex lines are fairly complicated mechanisms that are also susceptible to overstressing, and special care must be taken to make sure that the flex lines' boundary conditions are well posed. Currently, Europa Clipper HRS uses flex lines only on interconnects between the PM and the radiator and between the Vault and the ECIPA.
  - ***Elbow and tee joints*** are used where an interconnect line needs to turn or split within a very tight radius. They are standard parts made of 316L stainless steel. Due to sharp corners and edges inherent in these geometries, special nonlinear analysis was required to justify their use under the expected load cases.

- **Structural Attachments.** In order to properly constrain the HRS line structure on the spacecraft, both P-clamp brackets and field joint bulkheads were used as shown in Fig. 5. A bracket is defined as a member

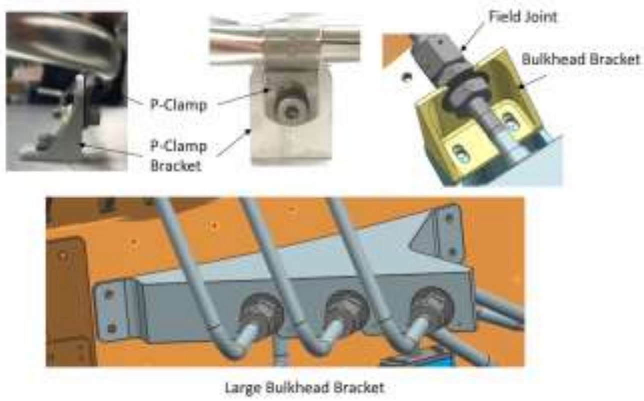


Figure 5. HRS P-clamp brackets and bulkhead fitting brackets

that supports the line using a p-clamp. A bulkhead is defined as a member that supports a field joint boundary where male and female fluid mechanical fittings interface. Furthermore, the attachment assemblies are categorized into two major types, according to design intent:

○ Brackets and bulkheads that serve as "rigid" divisions between sub-elements or modules

○ Brackets and bulkheads that support the lines within a given sub-element or module

The first category is important. While the analysis does take into account the relative flexibility between subsystems in the context of the entire system each time it is run, there is no guarantee that the structure in another sub-element is fully mature. By creating relatively rigid interfaces between major sub-elements, the analysis was able to limit effects between these sub-elements. This design approach was the key to simplifying the interfaces between APL's Propulsion Module and JPL's Avionics Module which have been at very different stages of development since the project's inception.

As for the second category, these are used to support interconnecting lines. A discussion on placement and analysis of these items is discussed later in this paper.

IV. Structural Environments and Requirements

There were several critical environments that were design driving for Europa Clipper's HRS:

- Acceleration and structural loading based on expected test and launch environments
- Thermal loads due to thermal cycling during ground testing and during the mission
- Ionizing radiation environments and Electrostatic Discharge (ESD) concerns

While the launch vehicle for Clipper is still under consideration, current options include the Space Launch System (SLS), Delta IV Heavy, or Falcon Heavy.

Table 1. Europa Clipper spacecraft flight system random vibration levels at the launch vehicle interface.

Frequency Hz	FA (Acceleration Spectral Density or Slope)	Qual/PF (Acceleration Spectral Density or Slope)
5–10	+ 6 dB/Octave	+ 6 dB/Octave
10–200	0.005 g^2 / Hz	0.01 g^2 / Hz
Overall	1.0 g_{rms}	1.4 g_{rms}

Qual: 2 minutes in each of the three orthogonal axes, one of which is the launch thrust axis.
PF/FA: 1 minute in each of the three orthogonal axes, one of which is the launch thrust axis.

A. Launch Loading Environments

There are a number of ways to develop launch load environments for a spacecraft. A typical way is to use a mass acceleration curve (MAC) to assign accelerations to components based on their mass. Another more rigorous way is to use a Modal Mass Acceleration Curve (MMAC.) The MMAC method applies accelerations based on the modal effective mass of the mode shapes of the spacecraft. Each spacecraft mode may be viewed as a single degree of freedom system with an effective mass; therefore, each mode can be driven (i.e., scaled) by the acceleration associated with its mass. Physical responses are obtained by Root-Sum-Squaring (RSS) the modal responses.

The accelerations applied to the mode shapes are derived from Coupled Loads Analysis, (CLA) which are generated to predict low frequency launch environments (<100 Hz.)

In addition to MMAC, the random vibrations environments (refer to Table 1) are used to evaluate workmanship of the assembled system, within a frequency range of 5 to 200 Hz. The Acceleration Spectral Density (ASD) curve is maximum at $0.01g^2$/Hz (at the base of the vehicle), and individual x, y, and z direction responses may be notched to protect specific flight hardware. Depending on the analysis, either MMAC or random vibrations are driving for margins of safety (MS).

Table 2. Temperature requirements for Europa Clipper.

HRS Sub Element	Qual/Protoflight Limits	Allowable Flight Limits	CC or PP Bakeout Limit
Avionics Module Vault	-35C to 70C	-20C to 50C	120C
RF Module Plate	-25C to 60C	-10C to 45C	120C
Prop Module Cylinders	-15C to 55C	0C to 35C	120C
Prop Module RWA	-15C to 55C	0C to 35C	120C
Prop Module REMS	-15C to 55C	0C to 35C	90C
Radiator	-110C to 45C	-95C to 25C	120C

B. Temperature Requirements

Temperature requirements varied between the elements with wider limits for the heat acquisition areas, narrower limits for the propulsion subsystem as conveyed by Table 2. The highest temperatures are invariably the Contamination Control (CC) or Planetary Protection (PP) bake out exposures (typical 1 time event prior to launch), and the lowest temperature was at the radiator, which has to survive down to the freezing point of CFC-11. Most HRS components were not sensitive to the temperature range. A notable exception is the Nusil CV 2946 bond, which due to its relatively low strength, showed low positive margins against thermal strains.

Table 3. Dielectric size requirements due to radiation environment (maximum permitted thickness as a function of total exposed area).

Total Exposed Surface Area	In Vault, Inside Chassis	In Vault, Outside of Chassis	Outside Vault, Outside Chassis	Outside Vault, Inside Chassis
Area < 3 cm^2	< 5 mm to any ground referenced conductor	< 3 mm to any ground referenced conductor	< 0.060" to any ground referenced conductor	Any size acceptable, as long as expected arcing will not cause damage, and area is less than indicated maximum
Area > 3cm^2	Same as above	Same as above	Same as above	Not acceptable

C. Radiation Environment Constraints

Radiation environment constraints were of special interest. Because of the intense radiation environment surrounding Jupiter, dielectric materials can readily accumulate charge. Given enough charge in a dielectric, discharge may occur and disrupt signals in nearby cables or possibly harm other surrounding components of the spacecraft. Typically, dielectrics such as G10 or Ultem 2300 are used to effectively isolate hot or cold plumbing from the underlying supporting structure as necessary, but use of these materials turned out to be impractical for Europa Clipper. Table 3 displays some of the strict set of guidelines provided by the project's Electrostatic Discharge (ESD) control plan, indicating the size of dielectrics allowed on any part of the spacecraft. However, where required low thermal conductivity titanium attachment hardware was substituted for the preferred dielectrics, and the team was able to sidestep the ESD concern.

D. Specific Mechanical Subsystem Requirements

Specific requirements for the mechanical HRS effort were not explicitly defined. However, since the thermal loop is a critical part of the spacecraft and a single point of failure for the mission, the implied requirements are that the Europa Clipper HRS must:

- Survive launch without detriment to the function of the system.
- Support thermal regulation throughout the duration of the mission.

V. Mechanical Properties, Safety Factors, and Analytical Approach

Table 4. Stress allowables used for HRS plumbing.[15,16]

Material	F_{ty} (MPa)	F_{tu} (MPa)	F_{su} (MPa)	Source
Al6063-T6	25 ksi (172)	30 ksi (207)	15 ksi (103)	AMS-QQ-A-200/9A
Al6063-T4	10 ksi (68.9)	19 ksi (131)	10 ksi (70.0)	AMS-QQ-A-200/9A
Al6061-T4	14 ksi (96.5)	35 ksi (241)	20 ksi (138)	ECOSTRESS Project data
Al6061-T651	37 ksi (255)	43 ksi (296)	28 ksi (193)	MMPDS
316L	26 ksi (179)	73 ksi (503)	50 ksi (345)	MMPDS

Reference from sources are in imperial units; the ksi values should be used for best accuracy. SI units rounded to 3 significant digits.

A. Allowables and Factors of Safety

The HRS uses standard materials and components. The metallic data was taken from standard references, or in the absence of a reliable reference, test data was gathered by this or previous projects. See Table 4 for a summary of relevant data.

Reliable Nusil CV 2946 material properties were not available. The Europa Clipper HRS team conducted its own Thermomechanical Analysis (TMA), Dynamic Mechanical Analysis (DMA), and lap shear tests over the full range of temperatures to get Ultimate Tensile Strength (UTS) allowable, equivalent elastic modulus (derived from energy modulus), and Coefficient of Thermal Expansion (CTE). Refer to Table 5 for values.

Table 5. Nusil CV 2946 material properties.

Lap Shear Bond Line	Temperature	B-Basis Lap Shear Strength (MPa)	Elastic Modulus (MPa)	CTE (µm/m/C)	Source
0.025" Al-Al	-110C	**1663 psi** (11.5)	**166,793 psi** (1.15×10^3)	**93.8 µin/in/F** (169)	JPL Test
0.025" Al-Al	RT	**148 psi** (1.02)	**2,900 psi** (20.0)	**93.8 µin/in/F** (169)	JPL Test
0.025" Al-Al	120C	**114 psi** (0.786)	**2,900 psi** (20.0)	**93.8 µin/in/F** (169)	JPL Test

Reference from sources are in imperial units as noted in parenthesis; these values should be used for best accuracy. SI units rounded to 3 significant digits.

Table 6. Europa Clipper project factors of safety.

Type	UTS FS	Yield FS	Fitting Factor	Use Cases
No Test FS	2	1.6	-	Used for HRS fittings and lines
Test FS	1.4	1.25	-	Used for some extrusion bolts and bonds
Bond	1.5	-	1.15	Used for Nusil CV 2946 Bonds
Internal Pressure	4	1.5	-	Used for pressurized lines

The factors of safety (FS) in Table 6 were used to do all the mechanical and stress analysis on Europa Clipper HRS. Test factors of safety are factors of safety that require a physical load test to justify their use. No test factors of safety are factors that need only be justified by analysis. In general, positive margins of safety must be maintained against these factors of safety (test or no test) for a design to be acceptable.

B. Analysis methodology for plumbing

In general, HRS's are secondary structures that must conform to the spacecraft that they are mounted on. As a result, they can experience significant displacements and stresses during vibration loading. For EC, the transfer lines are made from steel, while the majority of the thermal spreaders are made from aluminum. In accordance with the MMAC and Random Vibration analysis, the following guidelines were adhered toward the material stressing cases:

- Yield
    - 316L Steel Lines
        - Yield permitted, so long as UTS margins were positive and fatigue life was adequate
    - Al Extrusions
        - Only positive MS accepted for Yield
- UTS
    - Regardless of material, must have positive margins against UTS
- Fatigue
    - Any fatigue damage is kept low enough by design so that it is significantly less than 1.0 fatigue lifetime for the material (aluminum or steel)
    - Significant loading only occurs during launch, assuming contributions from
        - 2 minutes of random vibration in each x, y, and z axis in the current spacecraft Finite Element Model (FEM) configuration
        - 30 seconds of launch environment
    - In the analysis model, 5 load components accumulate fatigue damage on the HRS components. They are MMAC lateral and axial loads, and random vibration in the x, y and z directions. Each component imposes a certain level of fatigue damage and is expressed as a damage ratio to the required life of the material (knocked down by scatter factor of 4). Linear Miner's rule[17] (refer to equation 1) states that the total fatigue damage that is accumulated is equal to the sum of each individual damage endured by their respective load component:

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C \quad (1)^{17}$$

      where N is the required life (cycles), scatter factor, n_i is the expected life due to each load component i, and C is the total damage. By using this method, a conservative estimate of fatigue damage is made for each HRS plumbing component.
    - For conservatism, 3-σ element forces and stresses are assumed to occur at the maximum zero crossing frequency. Aluminum HRS components were analyzed using S-N curve from MMPDS to calculate predicted fatigue life (N_f) as a function of modified Goodman Stress (Seq), assuming stress

ratio of R = -1. The same S-N curve is reduced to simulate Al 6061-T4 properties in areas where T6 properties were not expected to be achieved. 316L HRS components were analyzed using a bilinear strain to failure curve, using material models based on either Smith-Watson-Topper[18], or Fatemi-Socie.[19] This bilinear curve approach allows the consideration of both mean stress and alternating strain, which can both be significant drivers in early yield onset austenitic steels such as 316L. The final fatigue damage calculation uses a life scatter factor of 4.0.

C. Analytical Model

To obtain loads to size the HRS, a system level NASTRAN[20] FEM was created and integrated with the complete model of the spacecraft (see Fig. 6). The integrated model is driven at the launch vehicle interface by the launch or random vibration environments provided in Table 1. HRS tubing components are modeled with 1D elements (CBAR, CBEAM, CBENDS) along their center lines, which are then physically offset using RBE2 elements to represent mounting brackets to the spacecraft. The RBE2 elements serve to capture moments on the lines due to the offset distance from the underlying mounting structure. A bar offset is used to model the neutral axis shift as the cross sectional geometry of the HRS plumbing abruptly changes between the aluminum thermal spreaders and steel interconnect tubing. CBUSH elements connect the RBE2 elements to RBE3 elements which can then create connectivity to the spacecraft skin nodes. Figure 7 shows how the thermal spreaders are represented in the analytical model.

Figure 6. Analytical model of HRS lines on Europa Clipper.

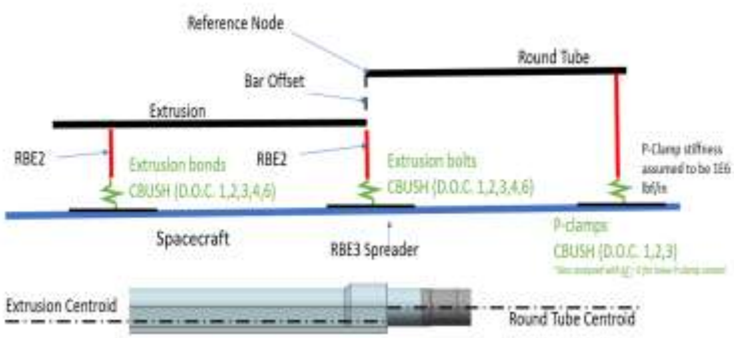


Figure 7. Representative analytical model segment for aluminum flanged extrusion with transition to stainless steel.

The system level HRS FEM is a mechanical model, and the loads carried by the HRS components are mechanical loads. Two sources of mechanical loads are possible:

1. Mass/inertia of the lines themselves, or
2. Interface loads from the spacecraft.

In general, spacecraft interface loads drive the majority of sizing and attachment locations of the HRS to the full structure. Locations where unsupported spans of HRS lines are excited by its own mass do exist, but are fewer. The overall challenge in designing the HRS system is the balance between decoupling the system from high interface loads versus placing enough attachments such that the lines' masses do not contribute to dynamic responses that can be detrimental.

VI. Design Challenges

A. Propulsion Module Sway and Bending

During launch loading, the PM is loaded both in line with the PM and orthogonally to the PM. The orthogonal loads tend to cause the PM to sway back and forth in a cantilever fashion. Since the thermal spreaders are installed vertically on the PM as shown in Fig. 8, the extrusions will tend to get strained when the PM structure begins to sway. Since the fluid lines are not intended to be primary structural members, it was determined that the most stressed portions of the extrusion joints should be allowed to slip in the vertical direction and thereby relieve some of the strain on the extrusion lines. To do this, the bolted joints on the extrusions at the bottom end of the spacecraft near the launch vehicle adaptor ring were designed to slip. When slipping a thermal spreader joint, two associated challenges arise:

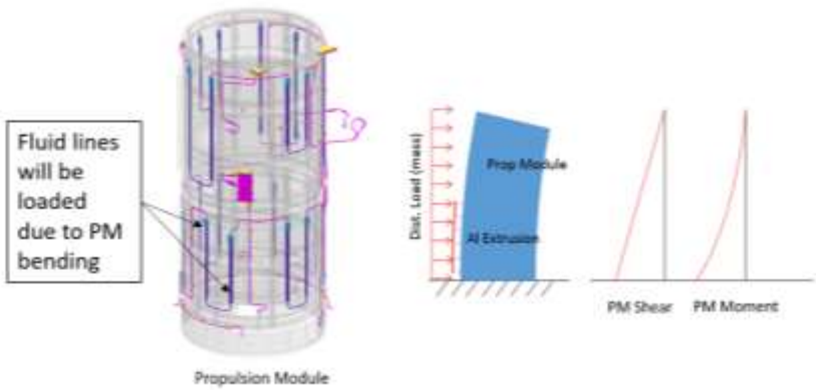


Figure 8. Propulsion Module bending leading to high stress in aluminum extrusions near launch vehicle interface.

1. Strain in Nusil bonded joint
2. Possible bolted joint bearing loads

The Nusil strain concern was mitigated by analysis. The amount of displacement in the PM that is inflicted on the bonded joint was the worst case Nusil mechanical strain, but it still showed positive MS.

For bolted joints, it is best practice not to load a threaded column in bearing load. To avoid bearing contact between the bolted plates and the threads, bolt clearance at the slipping joints must be guaranteed. Europa Clipper HRS uses slots for slipping joints. By using this approach, fasteners can be made to avoid bearing loads on the threads.

B. Transition Region from Steel Lines to Aluminum Extrusions

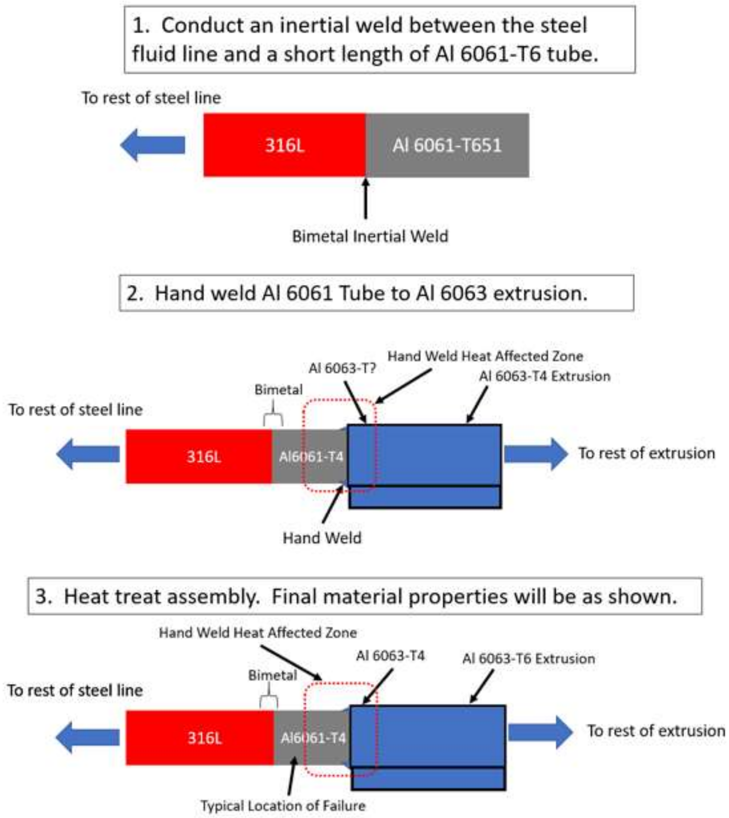


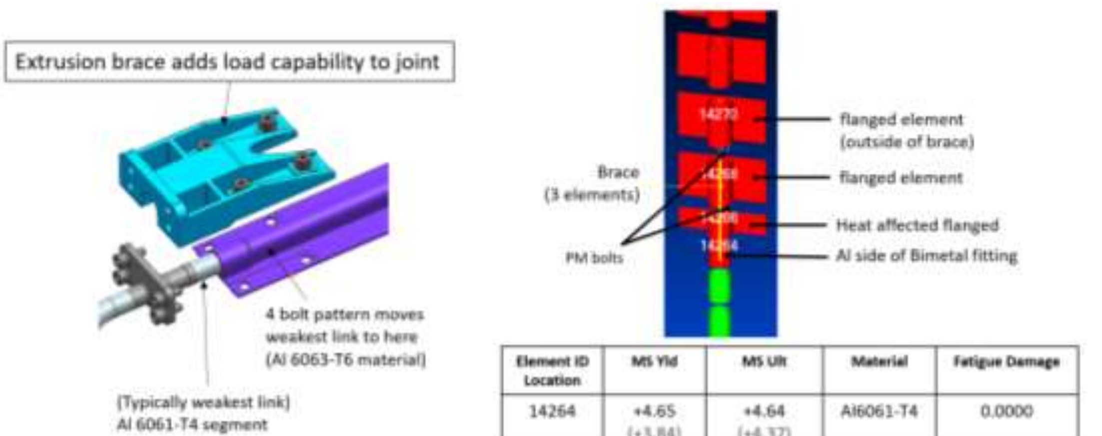
Figure 9. Stainless steel to aluminum extrusion welded transition region processing.

Once the PM swaying was identified as a high loading case for the extrusions, an additional challenge became obvious - how to best protect the transition regions between the aluminum extrusions and steel lines that contain several critical welded joints. There have been many misconceptions with respect to how the steel HRS lines are welded to the aluminum thermal spreaders and about the final allowable properties in the resulting aluminum to stainless steel transition region. For instance, it is often erroneously assumed that the transition is weakest because failure occurs at one of the specific weld locations (either the aluminum hand weld or the bimetallic inertial weld), when in fact these welds have never been the part of the transition region that fails under severe loading. In an effort to make the process and final product clear, a schematic was created.

Figure 9 shows that first, the 316L steel line is inertial-welded to an Al-6061-T651 segment and a bimetallic tube weld fitting is created. Then, the aluminum segment of the bimetallic fitting is hand welded to the end of the Al 6063-T4 extrusion. Due to the high heat of the hand weld, material tensile strength in the general vicinity of the hand weld will experience degraded temper- the Al 6061-T651 segment becomes Al 6061-T4, and the portion of the Al 6063 extrusion immediately adjacent to the hand weld has a temper that potentially may be lower than T4. In step 3, the entire assembly is heat-treated at 350oF for 8-10 hours and then air cooled in an attempt to restore T6 material properties. For conservatism, the 6061 bimetal segment is assumed to remain at T4, but the bulk of the extrusion recovers to a T6 condition except for the portion nearest to the hand weld, which is again for conservatism assumed to be in a T4 condition. Interestingly, the aluminum hand weld is actually significantly stronger than the Al-6061-T4 segment of the bimetal– and as a result the Al 6061-T4 segment has historically been the part of the transition region that breaks first under severe tensile loading due to its thin-walled cross sectional area being the smallest within the transition region. However, in the Europa Clipper HRS design, the lowest margins are experienced in the Al 6063-T4 region at the ends of the extrusion in the center of the four bolt pattern. This is because the bolt pattern makes this a very stiff part of the overall joint, which will always attract more load, but the Al 6063-T4 is still not a very strong material. As a result, MS are lowest in that region.

C. Weld Braces

Because there are weak members in the transition region between the aluminum extrusion and the steel line, it was



Element ID Location	MS Yld	MS Ult	Material	Fatigue Damage
14264	+4.65 (+3.84)	+4.64 (+4.37)	Al6061-T4	0.0000
14266	+3.85 (+3.99)	+2.26 (+2.30)	Al6063-T4	0.0000
14268	+0.31 (-0.11)	+0.29 (-0.05)	Al6063-T6	0.0026
14270	+0.30 (+0.29)	+0.25 (+0.26)	Al6063-T6	0.0022

Figure 10. Braces for stainless steel to aluminum extrusions weld transition.

recognized early in the project that it is desirable to have increased strength in this area. One option would have been to simply make the wall thickness of the aluminum section of the bimetal fitting thicker, but this was dismissed because it would simply displace the weak part of the region to another member, and eventually the welds themselves. Therefore, the team selected a more robust option to use a load carrying brace, as seen in Figure 10. The margins of safety are significantly increased with the brace in the transition region. Counterintuitively, with this approach, the smallest structural margins occur in the center of the 4-bolt pattern on the ends of the 6063-T6 extrusion, rather than within the typically weaker Al-6061-T4 segment. As noted previously, the region in the center of the bolt pattern experiences enough increased stress to make the margins smaller in that region due to constraints specific to the Europa Clipper HRS design, and not due to intrinsic material properties.

D. Nusil CV 2946 Bonded Joint Analysis

Nusil bonds are used to facilitate heat transfer to and from the thermal spreaders. Without a thermally conductive bond, the interface will not have deterministic heat transfer properties. To ensure that the bond remains a reliable conduit for heat transfer, it was critical that the effort acquire reliable properties for the bond material over the entire temperature range. The data gathered in Table 5 was used to analyze the thermal spreader bonds.

It is important to note that the peak mechanical and thermal stresses occur at different times. Maximum mechanical loads are applied during launch, when the temperature of all HRS plumbing is at or near room temperature. Maximum thermal stresses occur when there is no mechanical loading either while on the ground prior to launch, during an elevated temperature CC or PP bakeout or during the colder parts of the mission when there is little flow through the radiator circuit and the radiator structure can potentially realize temperatures as cold as -110^{o}C.

Figure 11 highlights the mechanical and thermal analysis approaches used for Nusil CV 2946 on the project. Mechanical stress was calculated both by FEM and hand calculations for strain. The equivalent strain analysis was

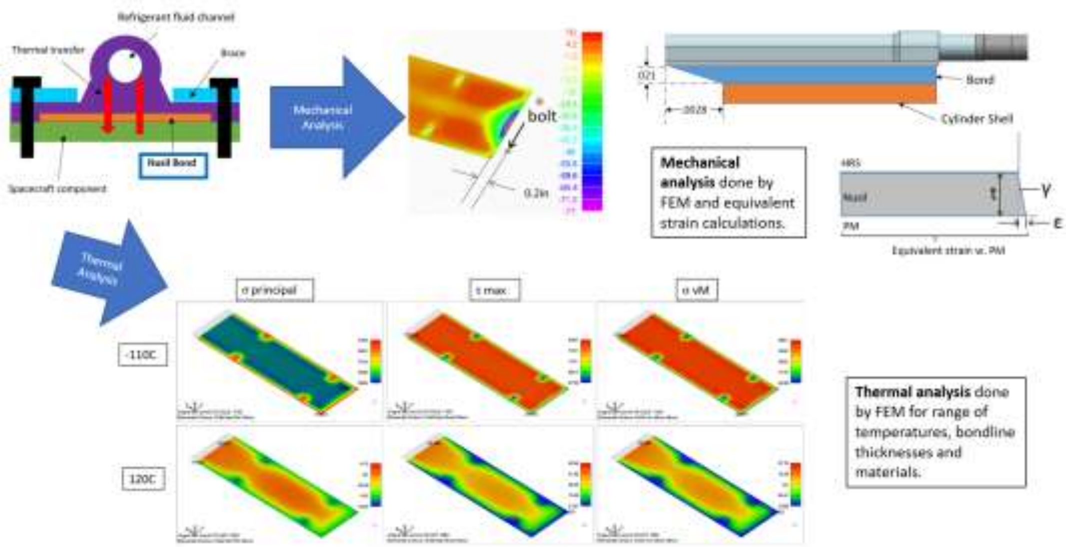


Figure 11. Nusil bond analysis: mechanical and thermal loading.

done by estimating the relative motion of the thermal spreader relative to the spacecraft from the NASTRAN analytical model. The relative displacement is then translated to effective shear strain in the Nusil CV 2946, expressed as γ as noted in Fig. 11. This shear strain was compared to the allowable principal strain derived from lap shear testing to arrive at the MS indicated.

In the analysis, it was found that the most sensitive parameter for bond integrity was bond thickness, with mechanical-derived Nusil loading increasing significantly with decreasing bond thickness. The Nusil bonds were less sensitive to thermally-derived loads, but tended to increase with increasing bond line thickness. This is because of the relatively high CTE of the Nusil CV 2946: with more volume of Nusil constrained within a lower CTE metal containment, there will be more strain for a larger temperature delta than for a smaller volume Nusil layer. Due to Geometric Dimensioning and Tolerancing (GD&T) constraints and thermal requirements, the bond line thickness under the thermal spreaders ranged from 0.010” to 0.030”, depending on the location. Positive margins were achieved for all applicable mechanical loading and temperature stressing conditions within this range of bond thicknesses.

E. Flex Lines

Flex lines (refer to Fig. 12) are used in areas where relative displacement is high enough that any standard interconnecting tube segment would be overstressed. Flex lines do offer more displacement capability than a comparable steel or aluminum line segment, but they are also complicated mechanical components that require detailed analysis to justify their use. As a result, Europa Clipper’s HRS team adopted a “need to use” attitude towards flex lines: if an interconnecting line could not easily close with

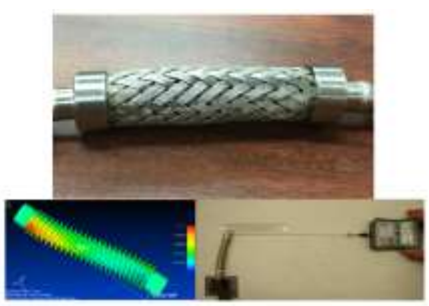


Figure 12. Flex line hardware and analysis.

Table 7. Flex line stiffness data.

Stiffness Direction	Stiffness	Source
Lateral	**20 lbf/in** (3.50x10³ N/m)	JPL, Test by P. Lytal
Axial	**5215 lbf/in** (9.13x10⁵ N/m)	JPL, Test by R. Van Schilfgaarde
Torsional	**1480 in-lbf/rad** (167 N-m/rad)	JPL, Test by R. Van Schilfgaarde

Reference from sources are in imperial units as noted in parenthesis; these values should be used for best accuracy. SI units rounded to 3 significant digits.

positive critical margins using a standard steel tube with several bends, a flex line was considered for use in the affected location. As noted before, the flex lines are currently only used in one location: at the radiator interconnects. In this location, special care is made that the mechanical mounting boundary conditions are well understood. Analysis was done using a flex line FEM model inherited from the Mars 2020 project, and stiffness data (refer to Table 7) was used from the ECOSTRESS project.

As in other steel elements, yield was tolerated while UTS MS were positive. Fatigue was monitored to ensure adequate life for the flex lines.

F. P-Clamp Placement and Thermal Isolation of Lines

There has been much discussion on how many supporting brackets are required to support a fluid line in either HRS or propulsion systems (refer to Fig. 13). Add too many supports, and the system loads can increase due to over-constraints; add too few supports and line loads can increase due to inertial loading. Previous projects have used rules of thumbs in terms of how many support points are advisable for a given length of tubing. Rather than follow a rule of thumb, with the advent of fast MMAC system-level analysis, the Europa Clipper HRS team used MMAC to guide the number and placement of the bracket locations. Some basic precepts were followed to help guide the analysis:

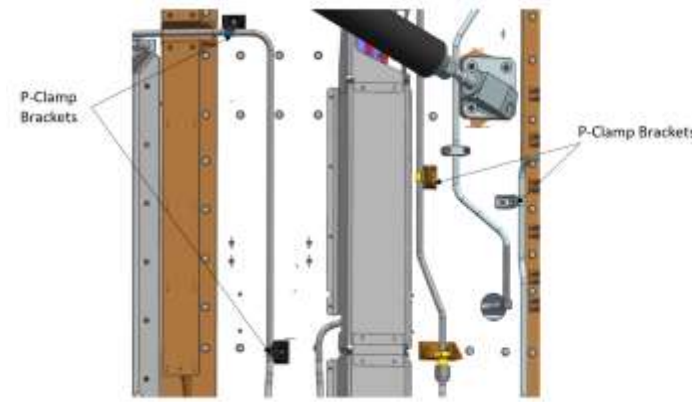


Figure 13. Placement of p-clamp structural supports.

- Loads should not be excessive; critical margins must be kept positive (as with any mechanical system)
- Displacements should be kept low, any relative displacement between hardware components should be kept below half the nominal distance between the hardware pieces
- Loads on lines were periodically checked with hand calculations

Another critical area of investigation related to bracket supports was the need for thermal isolation of several lines relative to the spacecraft including the HRS radiator supply and return lines and a segment of tubing immediately downstream of the RHB as shown in Fig. 14. In most other projects, a composite such as Ultem 2300 would be incorporated in the supporting bracketry designs to increase thermal resistance between the line and the structure. However, due to the radiation environment around Jupiter restricting the use of dielectrics, these HRS lines could not be isolated using the most thermally resistive materials. Significant effort was made to instead make the brackets out of titanium, using intricate designs to increase the thermal path length. This ended up being too time intensive to implement in this project. Instead, the brackets were designed the same as any of the standard aluminum brackets, except using titanium as the material to provide reduced but effective isolation.

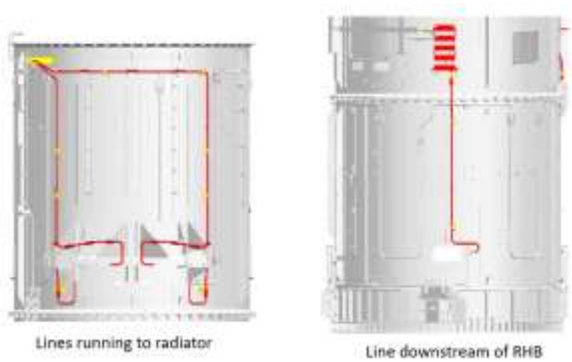


Figure 14. HRS lines where thermal isolation from the PM Structure is preferred

Figure 15 displays the critical yield, UTS, margins, as well as rated fatigue damage factors for the PM at the time of its design review. All the aluminum tubing stress margins are positive and healthy. Note that in general a fatigue factor less than 1 indicates that the total fatigue experienced by the structure is less than the total life of the material in the load case. The negative margins in yield for the steel lines is seen as acceptable because the UTS margins and

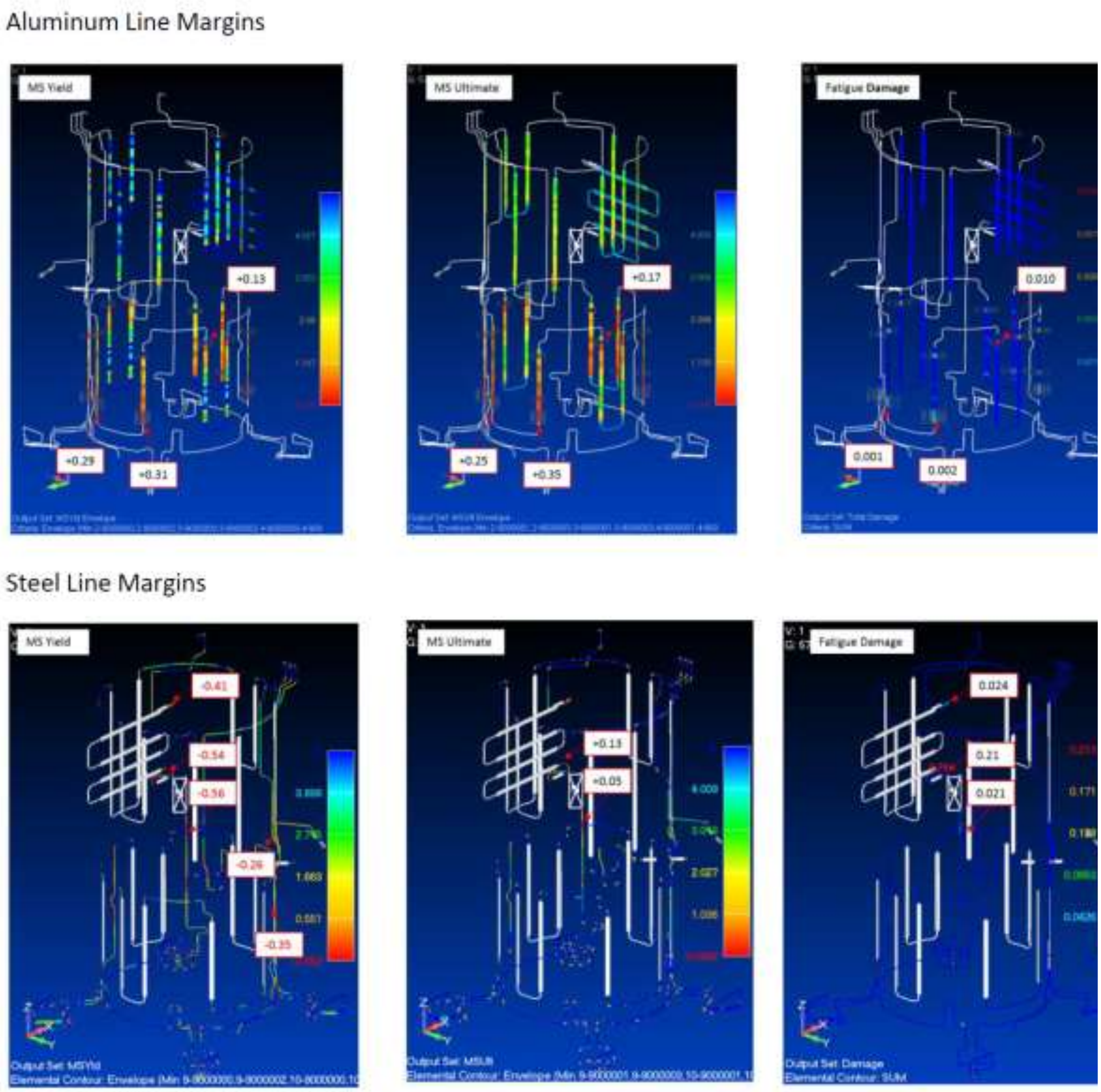


Figure 15. Summary of HRS structural margins and fatigue factors on the PM.

fatigue life are acceptable, and the steel is ductile -- no failure will result as a consequence of the indicated yielding in the steel lines.

VI. Lessons Learned

A. Flex lines

As noted earlier in this paper, flex lines are complicated. It is recommended that they are only used in locations where a standard interconnect tubing with a few inherent bends would be inadequate to mitigate the stress induced by the displacements, and where boundary conditions are well understood.

B. Elbows and Tee connectors

The 316L SS elbows are standard off the shelf parts that are commonly used in space system fluid loops. While commonly used, they do have very sharp edges that concentrate stress significantly. In our analysis, we allowed for negative yield margins while maintaining positive UTS margins (using a nonlinear strain analysis) and adequate fatigue life. This worked for Europa Clipper HRS, but if future projects want to use these pieces it is recommended that a similar analysis be done, and/or custom fittings without sharp edges be made.

C. Fluid mass accounted for in lines

When conducting the analysis for fluid lines, it is very important to represent the fluid mass in the lines. This seems obvious, but it can be easy to miss and could result in a significant difference in structural margins.

D. Nusil bond and proximity to ends of slipping extrusions

The extrusions slip most at the end of the lower cylinder extrusions. By pushing back the Nusil bonded region away from the end of the extrusions, we were able to greatly reduce the strain (and therefore stress) that the Nusil bond experiences. This was critical for getting positive stress margins in the Nusil bond layer.

E. Single Point Fasteners, P-Clamps and Brackets

Low mass fluid loop systems typically use standard single bolt fastened p-clamps and single bolt fastened brackets as shown earlier. On a component basis, single bolt mechanical designs are not ideal – as any applied load inflicts significant loads and moment against the single fastener bolted joint. However, assessing structural margins on a per bracket basis can be misleading. Any applied load (typically in the direction of the line) is reacted not just by a single bracket, but by the system of brackets, p-clamps, and extrusions as a whole. From this perspective, any applied load is shared and the system behaves more like an overall structure. Applied moments are also mitigated by bracket and clamp geometrical constraints that limit the amount of motion possible.

In addition, on Europa Clipper HRS, effort was made to ensure that individual brackets would not slip in shear or torsion by analysis, by implementing thicker hardware to help spread out the load to increase effective joint shear and torsion friction capability. Future projects should carefully consider loading against brackets, and perhaps consider using alternate hardware that uses more than a single fastener per interface to simplify the design and analysis of the joints.

VII. Conclusions

The mechanical design of Europa Clipper HRS is intended to fulfill the thermal requirements of the system, under the launch, thermal, and radiation environments imposed on the spacecraft. The design adapted heritage hardware from previous MPFL temperature regulated systems, such as on Mars Science Lab, Mars 2020, and ECOSTRESS to meet the unique requirements for the first such system designed to fly in orbit about Jupiter. With the design as outlined, the mechanical HRS design should fulfill its objectives and reliably serve as the critical thermal regulator of the Europa Clipper spacecraft. It is hoped by the authors that this paper will serve as a useful reference for future missions with an HRS architecture.

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